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13. ABSTRACT (Maximum 200 words) <p>In this study, we seek to improve our physical understanding of polarimetric thermal emission from random media where volumetric and surface scattering effects are significant. The foam-covered ocean surface provides a rich and complex environment for which to apply our theories and models. We aim to develop electromagnetic models that yield physical insights and provide accurate numerical results for the polarimetric passive remote sensing of the wind-driven, foam-covered ocean surface. A wind-driven ocean surface is characterized by both large- and small-scale roughness that are azimuthally dependent. This has significant effects on the polarimetric thermal emission and makes it possible to retrieve wind parameters from microwave remote sensing of the ocean. Moreover, under high wind conditions, the presence of foam over water surface could significantly enhance the polarimetric brightness temperatures of the ocean surface. Previous studies of foam emission based on theoretical models such as film-layer and solid water particles do not reflect realistic physical situation nor accurately predict foam emissivity for various observation angles. As a result, one must resort to empirical formulae derived from measurement data to incorporate foam emission in passive remote sensing studies of the ocean surface. Our goal is to provide a physically realistic, quantitatively accurate model for polarimetric thermal emission from the rough ocean surface that properly takes into account of foam contribution.</p>				
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FINAL REPORT

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OBJECTIVES

In this study, we seek to improve our physical understanding of polarimetric thermal emission from random media where volumetric and surface scattering effects are significant. The foam-covered ocean surface provides a rich and complex environment for which to apply our theories and models. We aim to develop electromagnetic models that yield physical insights and provide accurate numerical results for the polarimetric passive remote sensing of the wind-driven, foam-covered ocean surface. A wind-driven ocean surface is characterized by both large- and small-scale roughness that are azimuthally dependent. This has significant effects on the polarimetric thermal emission and makes it possible to retrieve wind parameters from microwave remote sensing of the ocean. Moreover, under high wind conditions, the presence of foam over water surface could significantly enhance the polarimetric brightness temperatures of the ocean surface. Previous studies of foam emission based on theoretical models such as film-layer and solid water particles do not reflect realistic physical situation nor accurately predict foam emissivity for various observation angles. As a result, one must resort to empirical formulae derived from measurement data to incorporate foam emission in passive remote sensing studies of the ocean surface. Our goal is to provide a physically realistic, quantitatively accurate model for polarimetric thermal emission from the rough ocean surface that properly takes into account of foam contribution.

APPROACH

1. Radiative transfer theory for foam-covered, wind-driven ocean surface

In our study, the ocean surface is divided into open surface and foam-covered surface, with the fractional surface area covered by the foam given by the empirical foam coverage factor F . The total thermal emission is taken to be the sum of these two contributions. We have previously studied thermal emission from the open, wind-driven rough ocean surface numerically [6]. Here, for computational efficiency, we use the two-scale model to calculate emission from the rough ocean

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surface. In the two-scale model, the ocean surface is separated into a large-scale roughness, characterized by the Cox-Munk slope distribution, and a small-scale roughness, characterized by the Durden-Vesecky power spectrum with hydrodynamic modulation. Scattering by the small-scale roughness is obtained using the small perturbation method, with local incident and scattering angles determined by the large-scale roughness. Kirchhoff's law is then used to relate bistatic scattering coefficients to the polarimetric brightness temperatures.

For foam-covered ocean, we formulate the thermal emission problem in terms of radiative transfer (RT) theory [7]. We model the foam as a layer of spherical air bubbles overlying the ocean surface. The bubble is coated with a thin shell of sea water. We assume here that the air bubbles are small compared to the electromagnetic wavelength so that Rayleigh scattering can be used to obtain the extinction and scattering properties of the foam layer. The RT equation for the Stokes vector is then solved using an iterative procedure, and we obtain closed form solution up the first order in scattering. Atmospheric absorption effects based on the millimeter-wave propagation model (MPM) [5] are also taken into account in our model.

2. Dense medium radiative transfer theory for foam emission

The model of foam scatterers described above is limited to small air bubbles that are sparsely distributed. In actual sea foam, the air bubbles are likely to be densely packed and could be present in a variety of sizes depending on formation and development conditions. To extend the validity of our model, we employ the dense medium radiative transfer (DMRT) theory [8,9] to calculate the foam emission. To incorporate coherent multiple scattering between the air bubbles, the analytical multiple scattering theory of quasi-crystalline approximation (QCA) [8,9] is used to calculate the extinction coefficient and scattering phase matrix of the foam layer. QCA represents a second-order truncation of the averaged multiple scattering equations and is able to capture accurately interactions between scatterers that are close to each other.

In contrast with traditional treatments of DMRT, the QCA-based DMRT computes the multiple scattering based on Mie scatterers instead of Rayleigh scatterers so that air bubbles with sizes comparable to the wavelength can be considered. For generality, the RT equation is solved exactly by using the numerical technique of discrete ordinate eigenanalysis (Gaussian quadrature). We consider bubbles with size distribution and clustering properties and examine how foam emission depends on these physical properties.

3. Improvements on foam distribution model and rough surface scattering calculations

The foam coverage factor has been assumed to be independent of wave slopes and wind direction. This is not true in actual sea foam. Since sea foam is formed from breaking waves, young foam is distributed more densely on the leeward side, while old foam is more uniformly distributed. We will study slope- and azimuthal-dependent foam distribution and examine its impacts on ocean emission. The anisotropic nature of such foam distribution would affect the azimuthal dependence of all four Stokes parameters, which is important in wind retrieval applications.

We will study more closely how rough ocean surface effects couple to the scattering in the foam layer. While the two-scale model works reasonably well in practice, it is a heuristic theory and ignores

multiple scattering aside from simple geometric shadowing. We propose to use the small slope approximation (SSA) expansion to treat both the large and small-scale roughness in the ocean surface. This provides a rigorous foundation to study rough ocean surface emission and its interactions with the foam scatterers.

WORK COMPLETED

Fully numerical solution for thermal emission from the open ocean surface has been obtained [6]. The ocean surface is modeled as a two-dimensional rough surface with impedance boundary condition and characterized by the Durden-Vesecky ocean spectrum. The method of moment (MoM) is used to solve the surface integral equations. The sparse matrix flat surface iterative approach (SMFSIA) is applied to reduce memory usage and speed up the computations. The numerical solutions provide useful comparisons with simple analytical approximations for rough surface scattering such as the small perturbation method (SPM) and physical optics (PO).

We formulated a radiative transfer (RT) based analytical theory that allows fast numerical computation of the polarimetric brightness temperatures for foam-covered, wind-driven ocean surface. Both volumetric (due to the foam particles) and surface (due to the rough ocean surface) scattering and absorption effects are incorporated in the model. The foam particles are modeled as air bubbles with thin shells of sea water. Attenuation constants due to scattering and absorption of the bubbles as well as the scattering phase functions are obtained and used as inputs into the RT model. Scattering by the rough surface with the Durden-Vesecky ocean spectrum is computed using SPM. Two-scale model based on the Cox-Munk slope distribution is also considered. We have compared the numerical results for the polarimetric brightness temperatures from our RT model with data obtained from Jet Propulsion Laboratory's WINDRAD experiment [3,4] and found excellent agreements.

In addition, a QCA-based dense medium radiative transfer theory has been applied to calculate the polarimetric thermal emission from dense distribution of foam particles. The effective propagation constant as well as the scattering and absorption coefficients are obtained by solving the generalized Lorenz-Lorentz law and generalized Ewald-Oseen theorem which follows from QCA. Utilizing the distorted Born approximation to compute the bistatic scattering cross section per unit volume from the foam particles, we also obtain the scattering phase matrix. In this way, we are able to include coherent multiple interactions between the closely packed foam bubbles [1,2] into the RT model. Exact numerical solution of the DMRT equation is obtained with the quadrature technique.

RESULTS

Numerical simulations of thermal emission from plain ocean surface show that azimuthal variation of the brightness temperature depends most sensitively on the high-frequency portion of the Durden-Vesecky ocean spectrum, a conclusion which also follows from the small perturbation method (SPM) and physical optics (PO). However, detailed comparisons between simulation and analytical results show that PO under-estimates the brightness temperature and its azimuthal variation, while SPM over-estimates the brightness temperature but yields the correct azimuthal variation.

We find good agreements between our radiative transfer model and the WINDRAD measurement results, which give the polarimetric brightness temperatures as a function of azimuthal angles for several looking angles. This is illustrated in Figure 1, which shows the comparison of the brightness temperatures between our models and the experimental data at a looking angle of 30 degrees. Note that the match between theory and observation is excellent for both the one-scale and two-scale rough surface models. However, the one-scale model is much faster to compute than the two-scale model since fewer numerical integrations are involved.

The overall brightness temperature is contributed by three portions: plain ocean surface, foam, and atmospheric layer. The interactions between the different regions are described by the specified boundary conditions. Our RT model shows that the brightness temperatures contributed to T_v and T_h by foam and atmosphere are about the same. The third Stokes parameter U decreases when considering the foam, since the vertically and horizontally polarized emissions from the foam are not correlated.

We have also computed the brightness temperatures resulting from foam emission using QCA-based dense medium radiative transfer theory. Because of the lossy nature of the sea water at microwave frequencies, the extinction of the foam layer is dominated by absorption; however, for larger bubble sizes, scattering can play a significant role in determining the foam emission. Coherent multiple scattering captured by QCA tends to enhance absorption and lower scattering attenuation when compared to independent scattering. Typical results show that the emissivity of the foam-covered ocean, in comparison with that of the open ocean surface, is dramatically increased to a value close to one, as was observed in past experiments.

IMPACT/APPLICATIONS

The polarimetric passive remote sensing theory applying to ocean wind direction detection has been verified by aircraft experiments, and is proposed for satellite applications. This theory was developed under the support of this grant. Instrumental in the development of satellite applications, Dr. Son Nghiem and Dr. Simon Yueh of Jet Propulsion Laboratory were supported by the previous ONR contracts of this continuing grant and obtained their doctor degrees at MIT.

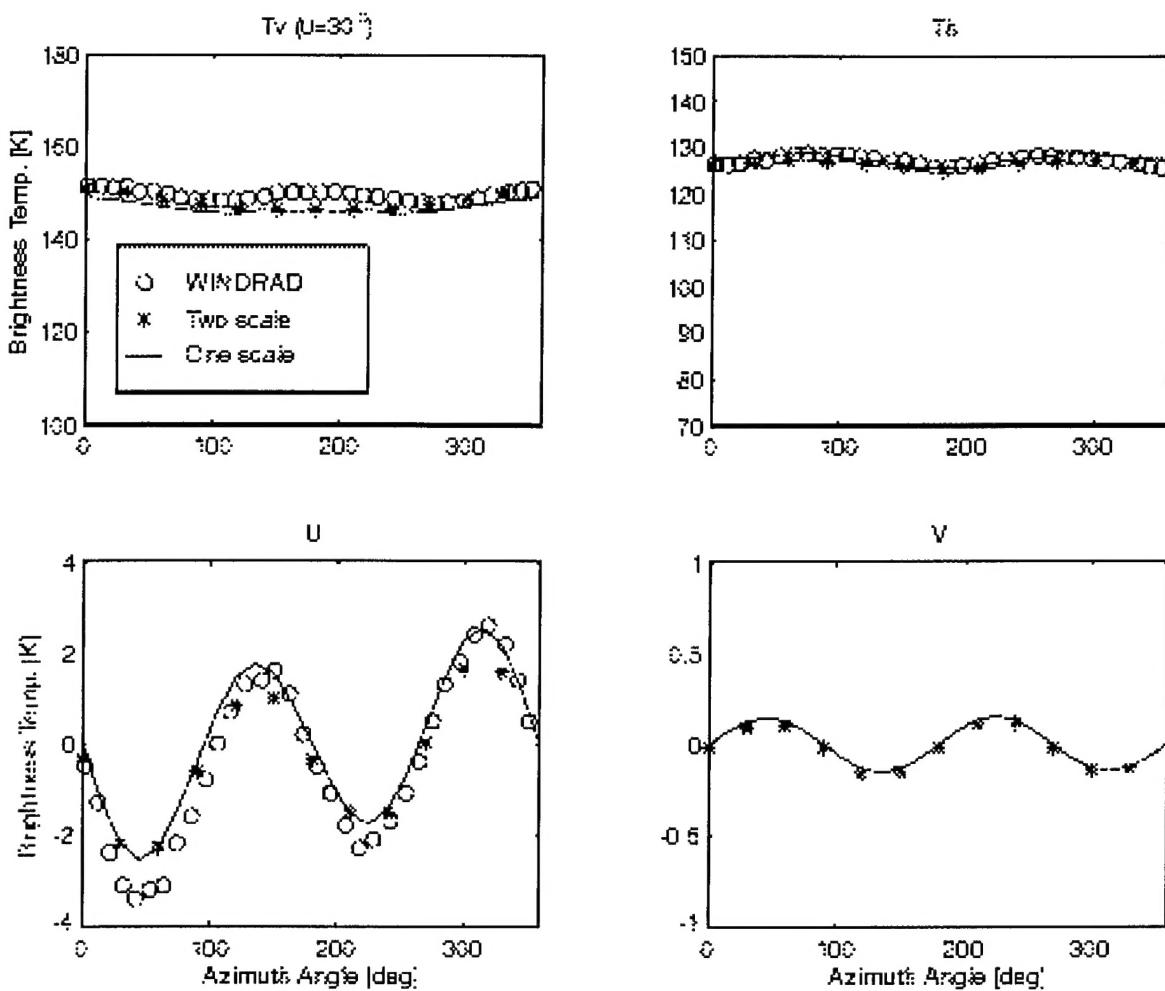


Figure 1. Comparison of the polarimetric brightness temperatures between results from our radiative transfer models and the WINDRAD experiment.
(Experimental data were not available for the fourth Stokes parameter V .)

TRANSITIONS

The theories and formulations as well as numerical methods developed for polarimetric passive remote sensing in this project provide fertile ground for exploring useful applications. The retrieval of wind parameters from satellites discussed in the previous paragraph is one such example. Dr. Joel Johnson of Ohio State University, who has contributed to this project at MIT, continues to be an active researcher of ocean remote sensing based on ideas developed from this project.

RELATED PROJECTS

In another project supported by ONR, Dr. Y. Zhang of MIT has investigated the active remote sensing of ship-like objects on the rough ocean surface. A hybrid approach has been developed that treat the two-dimensional rough surface with small perturbation method but allows exact numerical solution of scattering from the object.

PUBLICATIONS

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